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ON THE COEFFICIENTS OF THE RIEMANN MAPPING FUNCTION FOR THE COMPLEMENT OF THE MANDELBROT SET

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ABSTRACT. We denote the Mandelbrot set by \mathbb{M} , the Riemann sphere by $\widehat{\mathbb{C}}$ and the unit disk by \mathbb{D} . Let $f : \mathbb{D} \rightarrow \mathbb{C} \setminus \{1/z : z \in \mathbb{M}\}$ and $\Psi : \widehat{\mathbb{C}} \setminus \overline{\mathbb{D}} \rightarrow \widehat{\mathbb{C}} \setminus \mathbb{M}$ be the Riemann mapping functions and let their expansions be $z + \sum_{m=2}^{\infty} a_m z^m$ and $z + \sum_{m=0}^{\infty} b_m z^{-m}$, respectively. We consider several interesting properties of the coefficients a_m and b_m . The detailed studies of these coefficients were given in [1, 3, 4, 5, 8]. This is a partial summary of [11], which contains Zagier's observations (see [1]).

1. INTRODUCTION

For $c \in \mathbb{C}$, let $P_c(z) := z^2 + c$ and $P_c^{on}(z) = P_c(P_c(\dots P_c(z) \dots))$ be the n -th iteration of $P_c(z)$ with $P_c^{o0}(z) = z$. In the theory of one-dimensional complex dynamics, there is a detailed study of the dynamics of $P_c(z)$ on the Riemann sphere $\widehat{\mathbb{C}}$. For each fixed c , the (filled in) Julia set of $P_c(z)$ consists of those values z that remain bounded under iteration. The Mandelbrot set \mathbb{M} consists of those parameter values c for which the Julia set is connected. It is known that $\mathbb{M} = \{c \in \mathbb{C} : \{P_c^{on}(0)\}_{n=0}^{\infty} \text{ is bounded}\}$, compact and is contained in the closed disk of radius 2. Furthermore, \mathbb{M} is connected. However, its local connectivity is still unknown, and there is a very important conjecture which states that \mathbb{M} is locally connected (see [2]).

Let $G \subsetneq \mathbb{C}$ be a simply connected domain with $w_0 \in G$. Furthermore let $G' \subsetneq \widehat{\mathbb{C}}$ be a simply connected domain with $\infty \in G'$ which has more than one boundary point. Due to the Riemann mapping theorem there exist unique conformal mappings $f : \mathbb{D} \rightarrow G$ such that $f(0) = 0$ and $f'(0) > 0$ and $g : \mathbb{D}^* \rightarrow G'$ such that $g(\infty) = \infty$ and $\lim_{z \rightarrow \infty} g(z)/z > 0$ respectively, where $\mathbb{D} := \{z \in \mathbb{C} : |z| < 1\}$ and $\mathbb{D}^* := \widehat{\mathbb{C}} \setminus \mathbb{D}$. We call f (and g) the Riemann mapping function of G (and G').

Douady and Hubbard demonstrated in [2] the connectedness of the Mandelbrot set by constructing a conformal isomorphism $\Phi : \widehat{\mathbb{C}} \setminus \mathbb{M} \rightarrow \mathbb{D}^*$. Note that $\Psi := \Phi^{-1}$ is the Riemann mapping function of $\widehat{\mathbb{C}} \setminus \mathbb{M}$. We recall a lemma of Carathéodory.

Lemma 1 (Carathéodory's Continuity Lemma). *Let $G \subset \widehat{\mathbb{C}}$ be a simply connected domain and a function f maps \mathbb{D} conformally onto G . Then f has a continuous extension to $\overline{\mathbb{D}}$ if and only if the boundary of G is locally connected.*

This implies if Ψ can be extended continuously to the unit circle, then the Mandelbrot set is locally connected. This is the motivation of our study.

Jungreis presented an algorithm to compute the coefficients b_m of the Laurent series expansion of $\Psi(z)$ at ∞ in [7].

Key words and phrases. Mandelbrot set; conformal mapping.

Several detailed studies of b_m are given in [1, 3, 4, 8] and remarkable empirical observations are mentioned in [1] by Zagier. Especially a formula for b_m is given in [3]. Many of these coefficients are shown to be zero and infinitely many non-zero coefficients are determined.

In addition, Ewing and Schober [5] studied the coefficients a_m of the Taylor series expansion of the function $f(z) := 1/\Psi(1/z)$ at the origin. Note that f is the Riemann mapping function of the bounded domain $\mathbb{C} \setminus \{1/z : z \in \mathbb{M}\}$ and f has a continuous extension to the boundary if and only if the Mandelbrot set is locally connected.

In [12], Komori and Yamashita studied a generalization of b_m . Let $P_{d,c}(z) = z^d + c$ with an integer $d \geq 2$ and let $\mathbb{M}_d := \{c \in \mathbb{C} : \{P_{d,c}^{\circ n}(0)\}_{n=0}^{\infty} \text{ is bounded}\}$. Constructing the Riemann mapping function Ψ_d of $\widehat{\mathbb{C}} \setminus \mathbb{M}_d$, they analyzed the coefficients $b_{d,m}$ of the Laurent series at ∞ .

The author has been studying $b_{d,m}$ and the coefficients $a_{d,m}$ of the Taylor series at the origin of the function $f_d(z) := 1/\Psi_d(1/z)$ in [11].

In [12] and [11], there is a generalization of the results for $d = 2$, propositions for $d > 3$ and a verification of Zagier's observations.

In this paper, we focus on the case $d = 2$. Especially we mention the observations by Zagier and the asymptotic behavior of b_m .

2. COMPUTING THE LAURENT SERIES OF Ψ

Now we introduce how to construct Φ . This is established by Douady and Hubbard (see [1]).

Theorem 2. *Let $c \in \widehat{\mathbb{C}} \setminus \mathbb{M}$. Then*

$$\phi_c(z) := z \prod_{k=1}^{\infty} \left(1 + \frac{c}{P_c^{\circ k-1}(z)^2}\right)^{\frac{1}{2^k}}$$

is well-defined on some neighborhood of ∞ which includes c . Moreover, $\Phi(c) := \phi_c(c)$ maps $\widehat{\mathbb{C}} \setminus \mathbb{M}$ conformally onto $\widehat{\mathbb{C}} \setminus \overline{\mathbb{D}}$, and satisfies $\Phi(c)/c \rightarrow 1$ as $c \rightarrow \infty$. Thus $\widehat{\mathbb{C}} \setminus \mathbb{M}$ is simply connected and \mathbb{M} is connected.

Set $A_n(c) = P_c^{\circ n}(c)$ for simplicity. Applying the following proposition, we can calculate the coefficients b_m of Ψ .

Proposition 3 (see [1]).

$$A_n(\Psi(z)) = z^{2^n} + O\left(\frac{1}{z^{2^n-1}}\right).$$

Jungreis [7] presented an algorithm to compute b_m and calculated the first 4095 numerical values of b_m . Bielefeld, Fisher and Haeseler calculated the first 8000 terms in [1].

Ewing and Schober [4] computed the first 240000 numerical values of b_m , using an backward recursion formula in the following way.

Let n be a non-negative integer, and let

$$(1) \quad A_n(\Psi(z)) = \sum_{m=0}^{\infty} \beta_{n,m} z^{2^n-m} \text{ for } |z| > 1.$$

Using proposition 3, $\beta_{n,m} = 0$ for $n \geq 1$ and $1 \leq m \leq 2^{n+1} - 2$. Furthermore $\beta_{n,0} = 1$ for all $n \in \mathbb{N} \cup \{0\}$. Since $P_0(\Psi(z)) = \Psi(z)$, obviously $\beta_{0,m} = b_{m-1}$ for $m \geq 1$. Applying the recursion $A_n(z) = A_{n-1}(z)^2 + z$ to equation (1), we get

$$\sum_{m=0}^{\infty} \beta_{n,m} z^{2^n-m} = \sum_{m=0}^{\infty} \sum_{k=0}^m \beta_{n-1,k} \beta_{n-1,m-k} z^{2^n-m} + \sum_{m=2^n-1}^{\infty} \beta_{0,m-2^n-1} z^{2^n-m}.$$

For $m \geq 2^n - 1$, we compare the coefficients of the right and left-hand side. Hence

$$\beta_{n,m} = \sum_{k=0}^m \beta_{n-1,k} \beta_{n-1,m-k} + \beta_{0,m-2^n-1}.$$

Since $\beta_{n-1,0} = 1$ and $\beta_{n,m} = 0$ for $n \geq 1$ and $1 \leq m \leq 2^{n+1} - 2$, we obtain the following formula:

$$\beta_{n,m} = 2\beta_{n-1,m} + \sum_{k=2^n-1}^{m-2^n+1} \beta_{n-1,k} \beta_{n-1,m-k} + \beta_{0,m-2^n-1} \text{ for } n \geq 1 \text{ and } m \geq 2^n - 1.$$

This is the forward recursion to determine $\beta_{n,m}$ in terms of $\beta_{j,k}$ with $j < n$. A corresponding backward recursion formula is derived to be

$$\beta_{n-1,m} = \frac{1}{2} \left(\beta_{n,m} - \sum_{k=2^n-1}^{m-2^n+1} \beta_{n-1,k} \beta_{n-1,m-k} - \beta_{0,m-2^n-1} \right).$$

The formula gives $\beta_{m,n}$ in terms of $\beta_{j,k}$ with $j > n, k \leq m$. If n is sufficiently large, then $\beta_{n,m} = 0$ for a fixed m . Hence, using this backward recursion formula, we can determine $\beta_{j,m}$ for all j .

Example 4. Considering $b_0 = \beta_{0,1} = (0 - \beta_{0,0})/2 = -1/2$, $b_1 = \beta_{0,2} = (0 - \beta_{0,1}^2 - \beta_{0,1})/2 = 1/8, \dots$ yields

$$\Psi(z) = z - \frac{1}{2} + \frac{1}{8z} - \frac{1}{4z^2} + \frac{15}{128z^3} + \frac{0}{z^4} - \frac{47}{1024z^5} - \frac{1}{16z^6} + \frac{987}{32768z^7} + \dots$$

One can make a program for this procedure and derive the exact value of b_m , because b_m is a binary rational number.

Theorem 5 (see [4]). *If $n \geq 0$ and $m \geq 1$, then $2^{2m+3-2^{n+2}} \beta_{n,m}$ is an integer. In particular, $2^{2m+1} b_m$ is an integer.*

The coefficient a_m is also a binary rational number, since

$$a_m = -b_{m-2} - \sum_{j=2}^{m-1} a_j b_{m-1-j} \text{ for } m \geq 2.$$

Remark 6. In [1] Zagier made an empirical observation about the growth of the denominator of b_m , which we are going to mention in the next section.

Komori and Yamashita computed the exact values for the first 2000 terms in [12]. In [11], the author made a program to compute the exact values of b_m by using C programming language with multiple precision arithmetic library GMP (see [6]), and the first 30000 exact values of b_m were determined.

3. OBSERVATIONS BY ZAGIER

Based on roughly 1000 coefficients, Zagier made several observations. In this paper, two of them are mentioned. We write $m = m_0 2^n$ with $n \geq 0$, m_0 is odd.

Observation 7 (see [1]). It is $b_m = 0$, if and only if $m_0 \leq 2^{n+1} - 5$.

One direction of this statement has been proven in [1] and separately from that in [8].

Theorem 8. *If $n \geq 2$ and $m_0 \leq 2^{n+1} - 5$, then $b_m = 0$.*

It is still unknown whether the converse of this theorem is true. In [4], the only coefficients which have been observed to be zero are those mentioned in this theorem. In this publication Ewing and Schober proved the following theorem about zero-coefficients of a_m .

Theorem 9 (see [5]). *If $3 \leq m_0 \leq 2^{n+1}$, then $a_m = 0$.*

The truth of the converse of this theorem is unknown. They reported that their computation of 1000 terms of a_m has not produced a zero-coefficient besides those indicated in theorem 9.

Now we consider the growth of the power of 2. For every non-zero rational number x , there exists a unique integer v such that $x = 2^v p/q$ with some integers p and q indivisible by 2. The 2-adic valuation $\nu_2 : \mathbb{Q} \setminus \{0\} \rightarrow \mathbb{Z}$ is defined as:

$$\nu_2(x) = v.$$

We extend ν_2 to the whole rational field \mathbb{Q} as follows,

$$\nu(x) = \begin{cases} \nu_2(x) & \text{for } x \in \mathbb{Q} \setminus \{0\} \\ +\infty & \text{for } x = 0. \end{cases}$$

Due to theorem 5, if $b_m \neq 0$ then $b_m = C/2^{-\nu(b_m)}$, where C is an odd number. Note that $\nu((2m+2)!) \leq 2m+1$ for a non-negative integer m .

Observation 10 (see [1]). It is $-\nu(b_m) \leq \nu((2m+2)!)$ for all m . Equality attained exactly when m is odd.

In [12] a theorem for $b_{d,m}$ which includes this observation was presented. However, d has to be prime and not an arbitrary integer as it was originally stated.

Corollary 11. *It is $-\nu(b_m) \leq \nu((2m+2)!)$ for all m . Equality attained exactly when m is odd.*

For a_m we have the following:

Corollary 12. *It is $-\nu(a_m) \leq \nu((2m-2)!)$ for all m . Equality attained exactly when m is odd.*

The generalization of these result is given in [11].

4. OBSERVATION FOR THE ASYMPTOTIC BEHAVIOR OF b_m

The result which Ewing and Schober obtained shows that the inequality $|b_m| < 1/m$ holds for $0 < m < 240000$. If there exist positive constants c and K such that the inequality $|b_m| < K/m^{1+\epsilon}$ holds for any natural number m , this would imply its absolute convergence and give that the Mandelbrot set is locally connected. Furthermore, such a bound imply Hölder continuity (see [1]). However it is not valid because of the following claim given in [1].

Claim 13. *There is no Hölder continuous extension of Ψ to $\overline{\mathbb{D}}$.*

On the other hand, the coefficients b_m satisfying $|b_m| \geq 1/m$ have not been found yet.

The author focused on the local maximum of $|b_m|$ and considered the period of Jungreis' algorithm. The observation below for the behavior of b_m can be made.

Observation 14 (see [11]). For fixed $1 \leq n \leq 7$, the maximum value of $|b_{2^{2n}-2}|$, $|b_{2^{2n}-1}|$, \dots , $|b_{2^{2(n+1)}-3}|$ is $|b_{2^{2n}-2}|$. Furthermore, the sequence $|b_{2^2-2}|$, $|b_{2^4-2}|$, $|b_{2^6-2}|$, \dots , $|b_{2^{2n}-2}|$, \dots is strictly monotonically decreasing.

It is still unknown whether it would be true for every n , and the behavior of $\{|b_{2^{2n}-2}|\}$ is the material of further research.

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